Coronal Jets Confined by Coronal Loops

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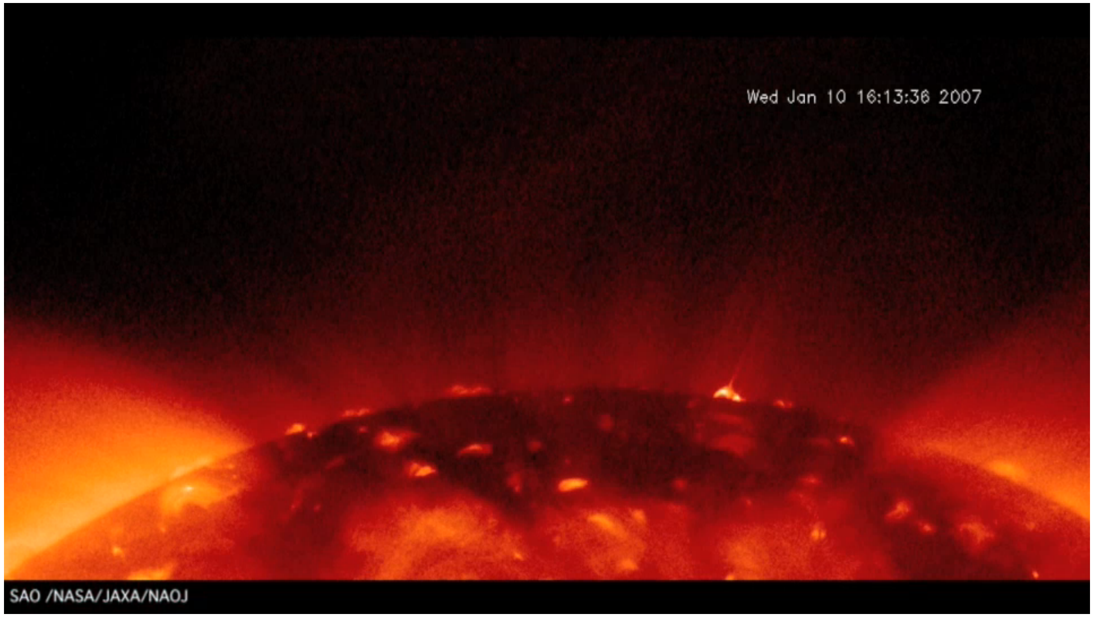
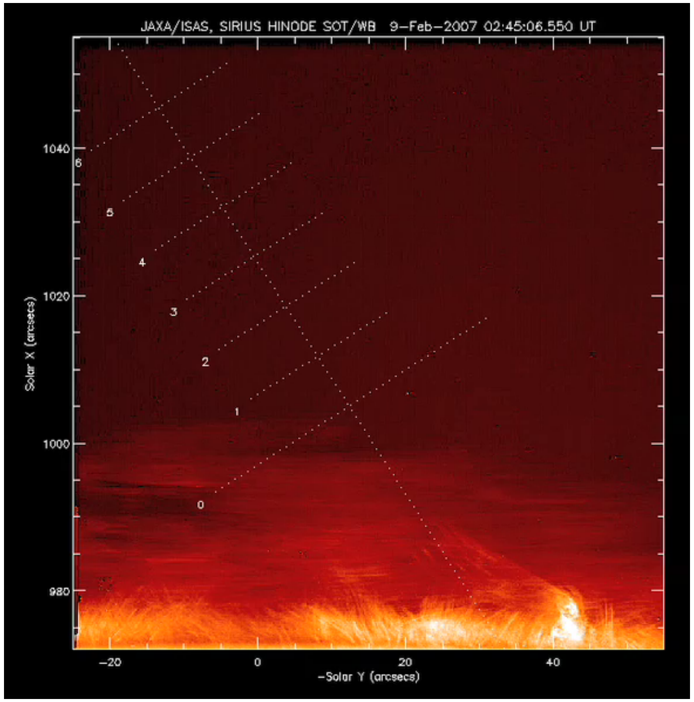
Observations

Open-field Jets

Cirtain et al. (2007)



Liu et al. (2009)

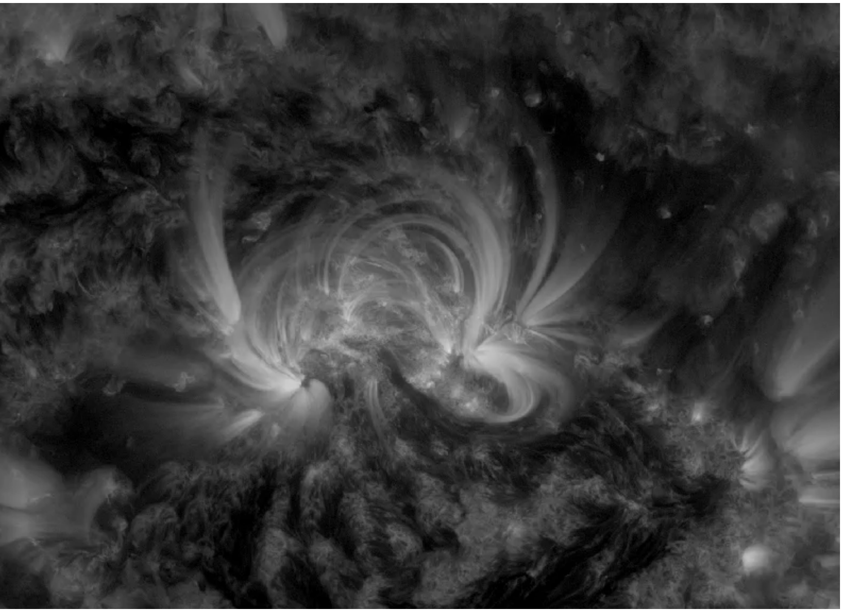


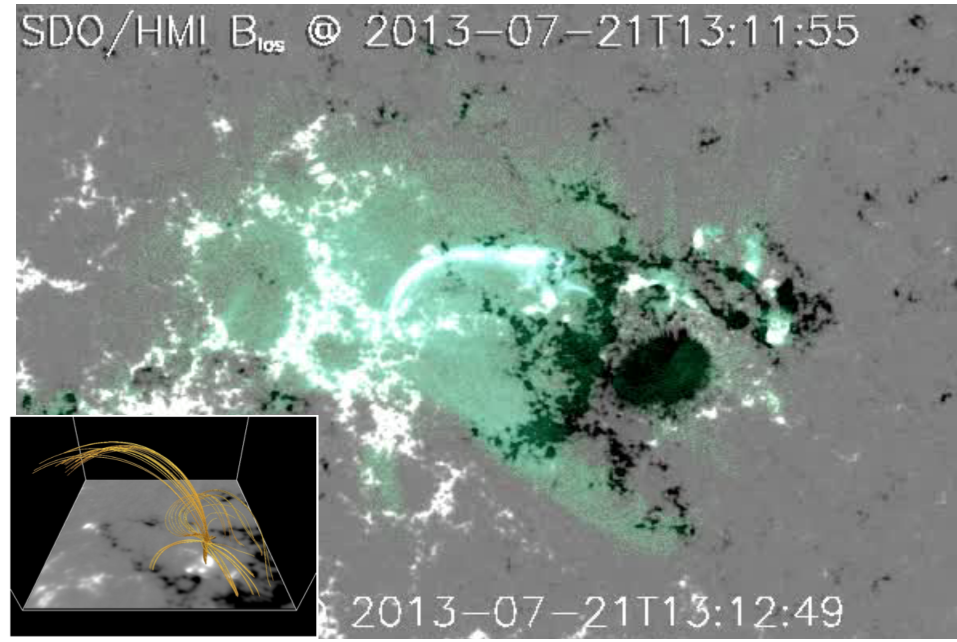
- Prolific in polar coronal holes.
- Base brightening and quasi-radial spires.
- Often exhibit helical motions.

Observations

Closed-field Jets

Cheung et al. (2015)



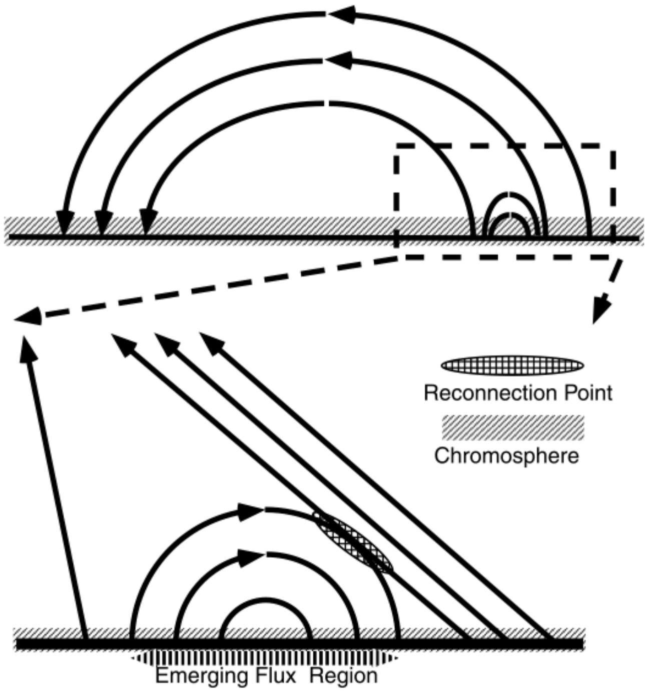


- Often within or nearby active regions.
- Some large jets in diffuse quiet sun field.
- Above parasitic polarities: 3D null field.

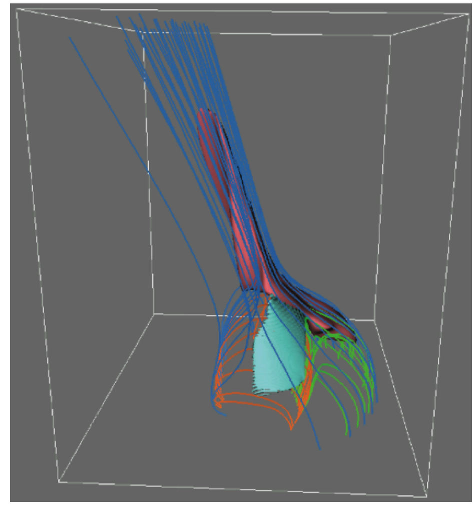
- Guided along the curved magnetic field
  -> jet expands & contracts.
- Often show helical motions.

Jet Generation Models

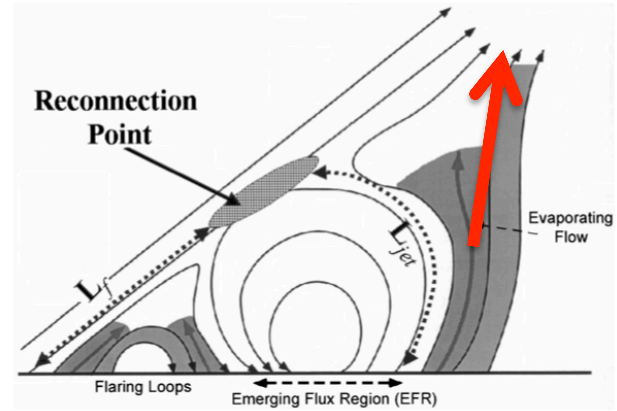
Shimojo et al. (2001)



Moreno-Insertis et al. (2008)



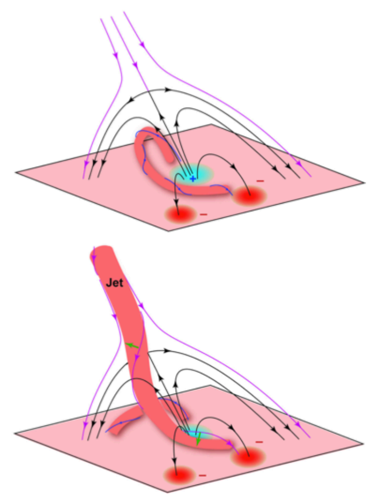
Shimojo & Shibata (2000)



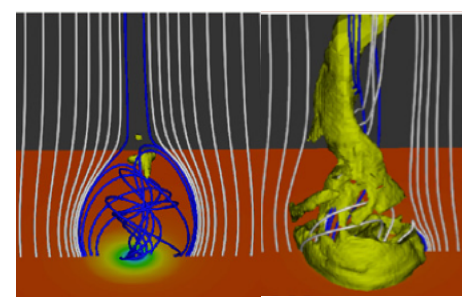
- Reconnection between quasi-open & closed field.
- Reconnection necessary, but may not always be the driver.

  1. Reconnection jet (magnetic tension).
  2. Evaporation (pressure gradient).
  3. Alfven waves (magnetic tension).

Filippov et al.(2015)

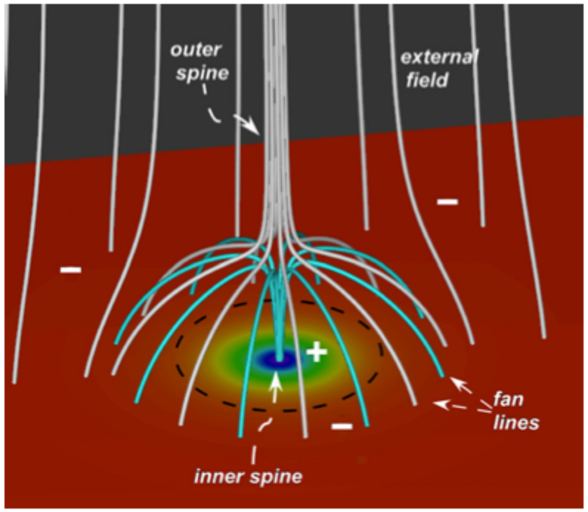


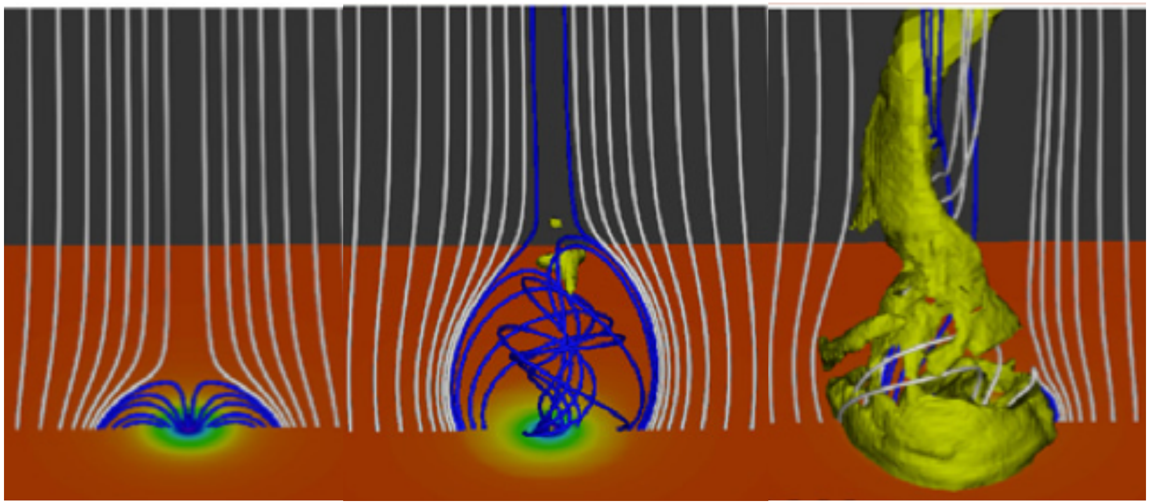
Pariat et al.(2009)



Embedded Bipole Model

Pariat et al. (2009)

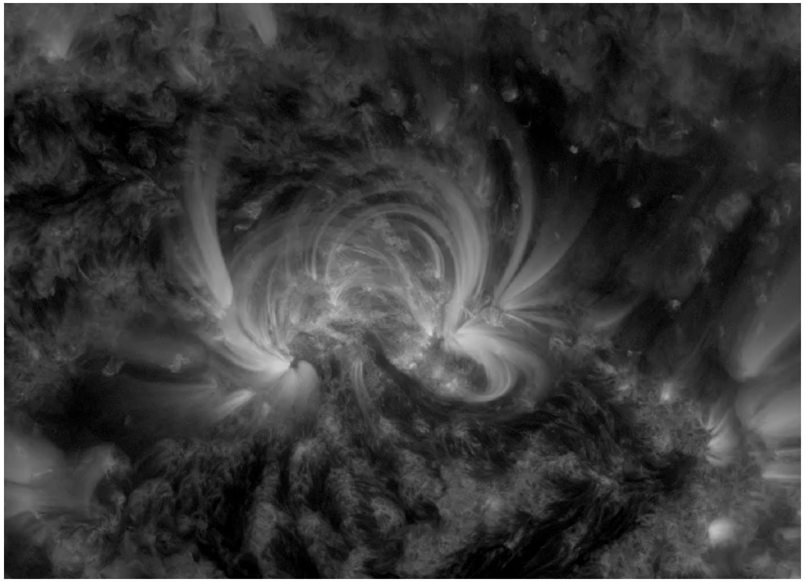




- Pre-existing parasitic polarity – potential field.
- Photospheric driving injects free energy.
- Reconnection initially inhibited by symmetry (similar with small inclines, Pariat et al. 10, 15)
- Kink-like instability breaks the symmetry, generating fast reconnection and an untwisting jet.
- System relaxes as twist propagates away.

Questions

- Will the same mechanism work in closed field configurations?
- To what extent does it reproduce the observed behaviour, i.e.:



- What happens to the confined jet?
- Do jets behave differently along long & short loops?
- Wide variety of loop lengths vs jet sizes.

→ Parameter study needed!

MHD Simulations

- Place a parasitic polarity in a dipole field.
- Two natural length scales:
  N – width of dome region
  L – foot point distance of
  background field

- Using the ARMS code to solve:

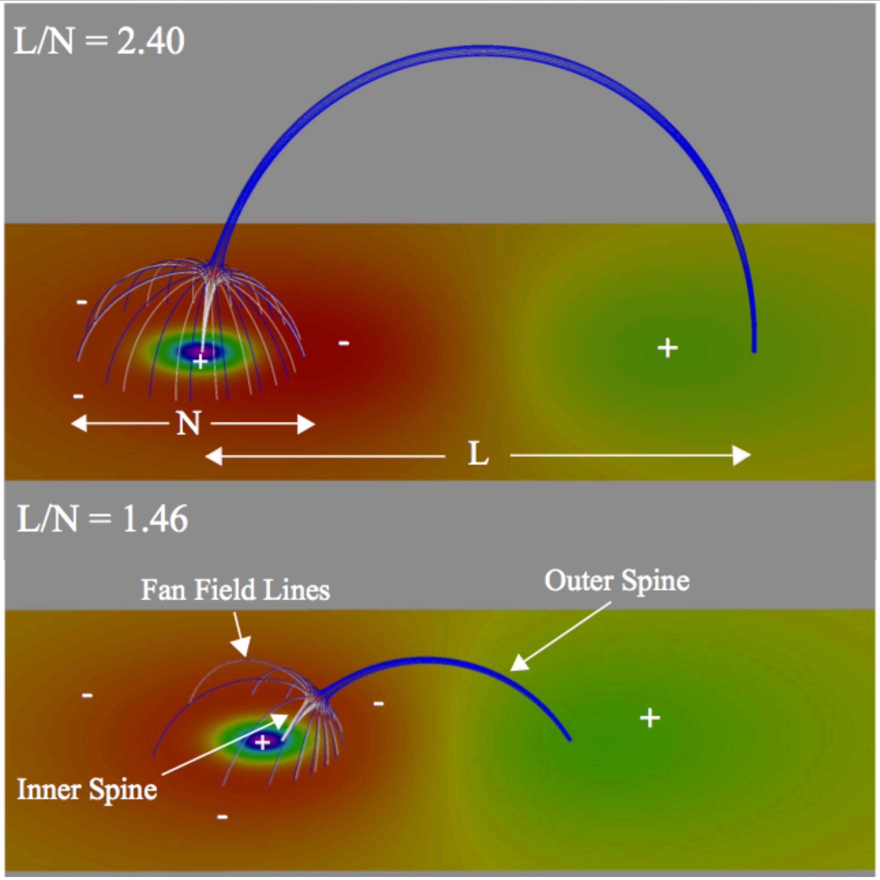
$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \mathbf{v}}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}\mathbf{v}) + \boldsymbol{\nabla} P - \frac{(\boldsymbol{\nabla} \times \mathbf{B}) \times \mathbf{B}}{\mu_0} = 0,$$

$$\frac{\partial U}{\partial t} + \boldsymbol{\nabla} \cdot (U \mathbf{v}) + P \boldsymbol{\nabla} \cdot \mathbf{v} = 0,$$

$$\frac{\partial \mathbf{B}}{\partial t} - \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B}) = 0.$$

Numerical resistivity

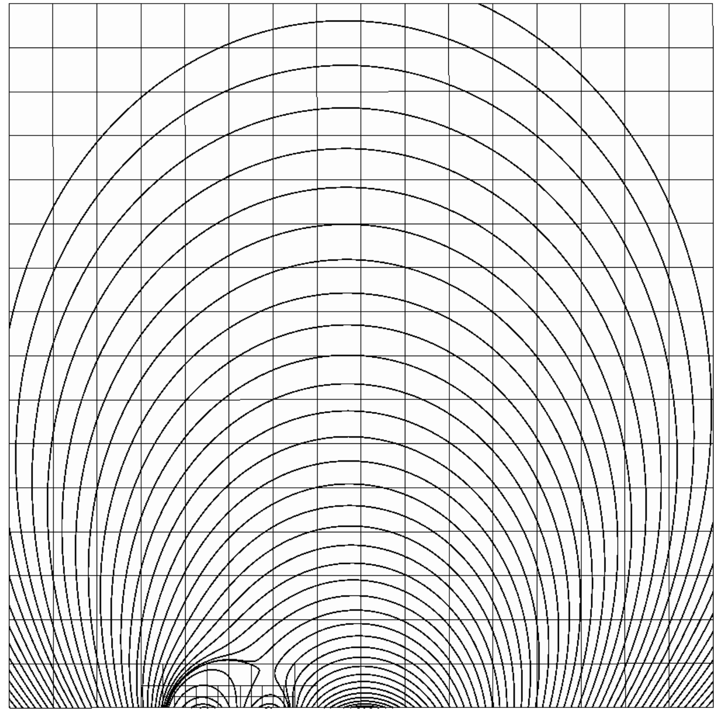


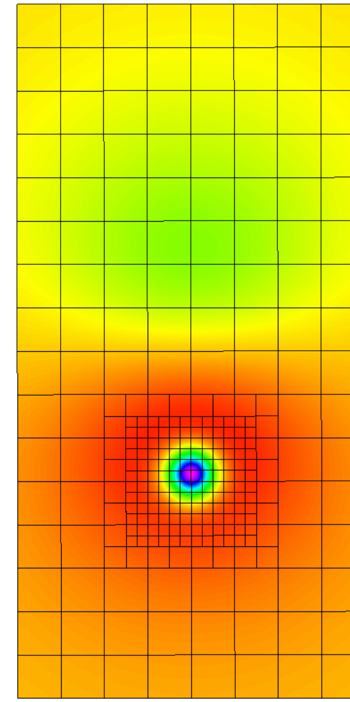
- Coronal loops and jets observed at many scales – so we use non-dimensionalised units.
- Cartesian; P, rho, T = const.; no gravity. Closed boundaries.
- N ~ 7Mm, B_{pp} ~ 210 G, B_{back} ~ 40 G (AR scaling)
- Parameter range: L/N = [1.0, 2.7]

MHD Simulations

Grid

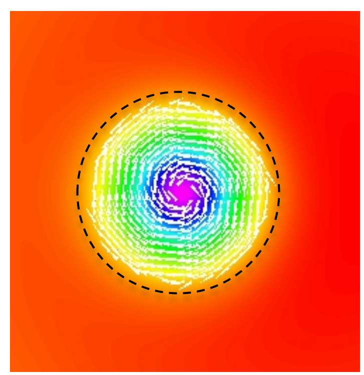
- Additional resolution at jet base to resolve driving.
- Each cell: 8x8x8 grid cells.
- Grid further adapts in regions of high current.

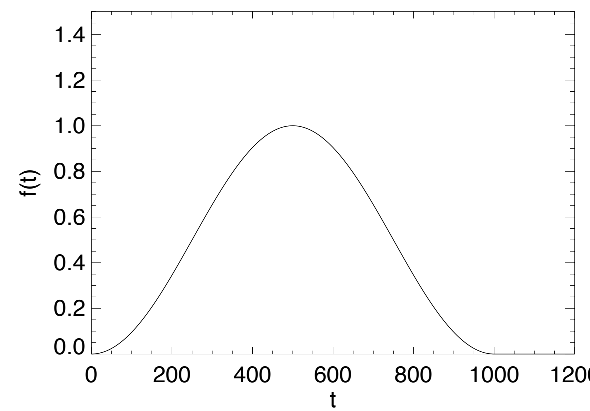




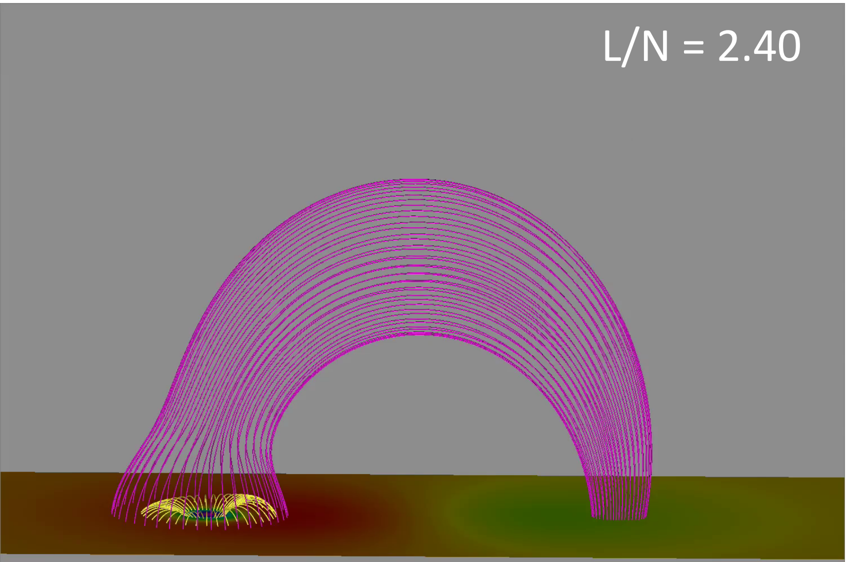
Driving

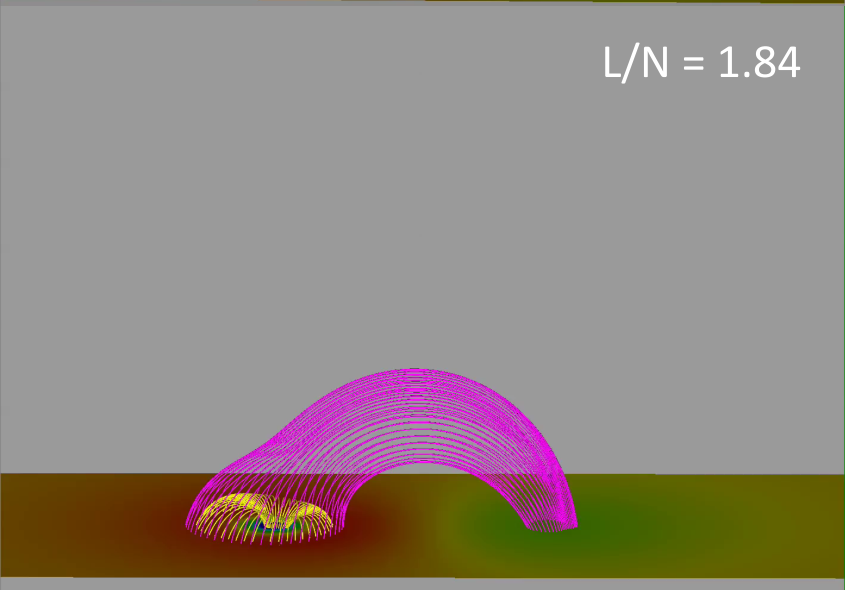
- Rotate sub-sonically/sub-alfvenically the parasitic polarity to build stress.
- Finite period
  (1000 sec, AR scaling)

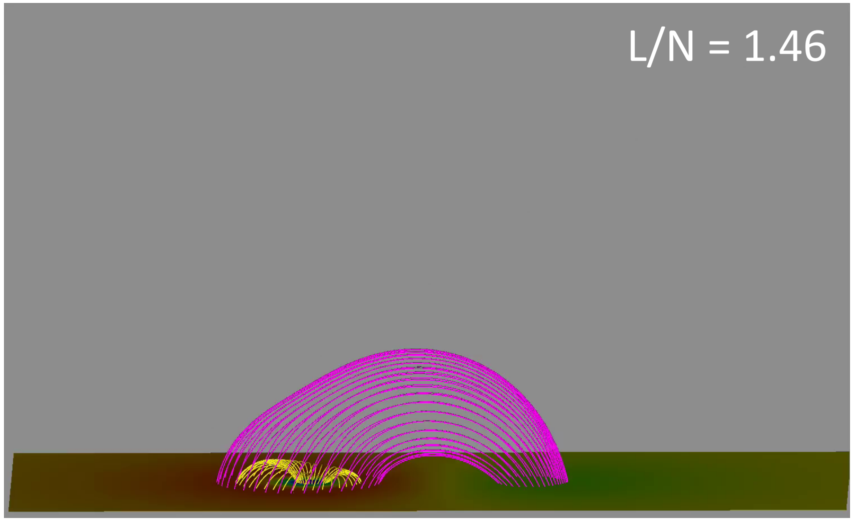




Jet Behaviour







- Velocity isosurface - Red: towards, Blue: away.
- AR values: iso (140 kms^{-1}), red/blue (100 kms^{-1})
- |J| - light blue contours.

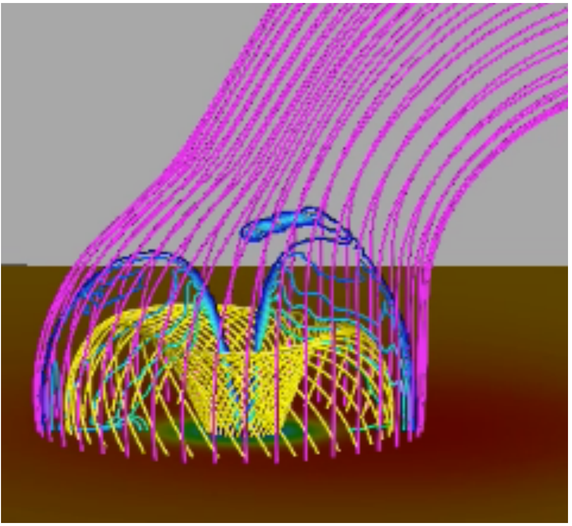
Long loop:

- Twist builds before kink-like onset and helical jet – similar to open-field case.
- Jet expands & contracts as it follows loop.
- Released twist trapped along loop.

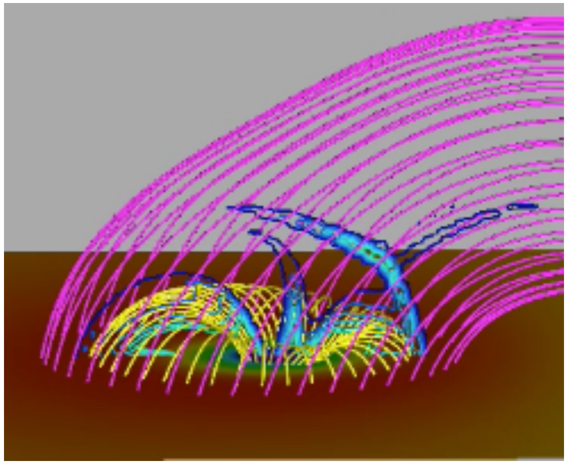
Shorter loops:

- Weak reconnection in buildup phase.
- Weaker, shorter more compact jets.
- Jet flow interaction.

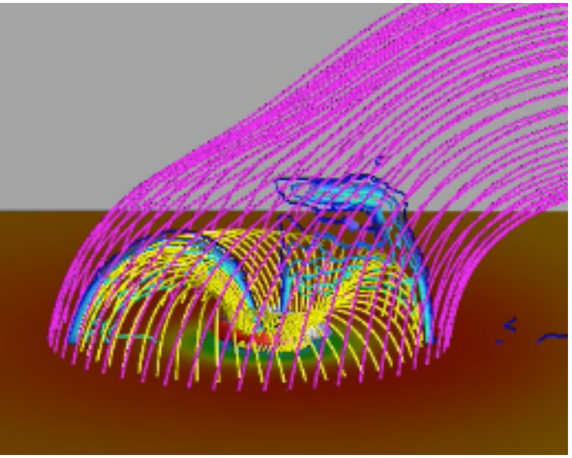
Jet Behaviour



L/N = 2.40



L/N = 1.46



L/N = 1.84

Reducing L/N ratio
= higher local inclination angle
= earlier current sheet formation and reconnection.

- Early reconnection is slow, giving weak outflows.
- Impulsive jet outflow occurs after kink onset.
- Local outflow speeds similar in each simulation.

Jets & Reconnection

The Squashing factor (Q)

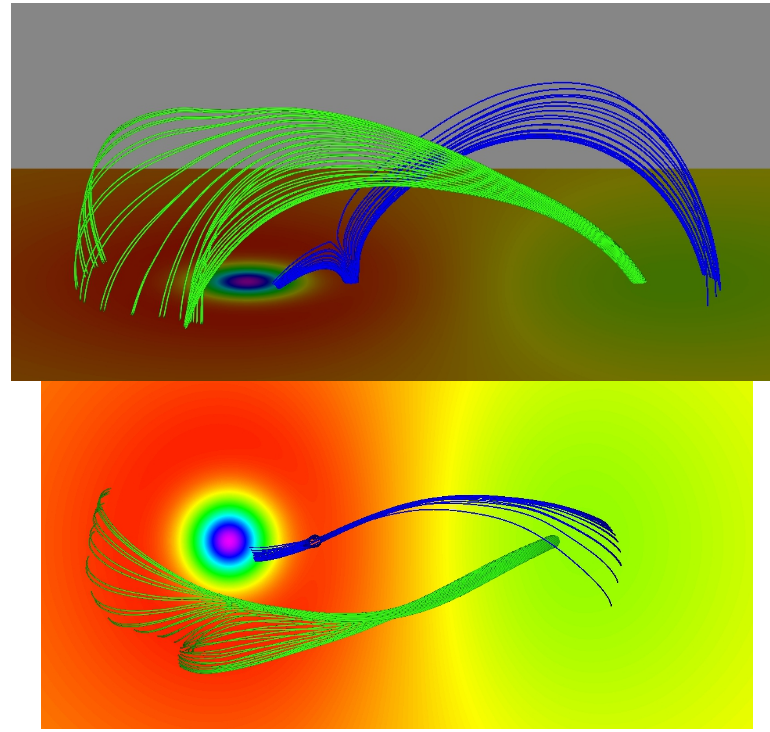
$$X = X(x,y) \quad \& \quad Y = Y(x,y)$$

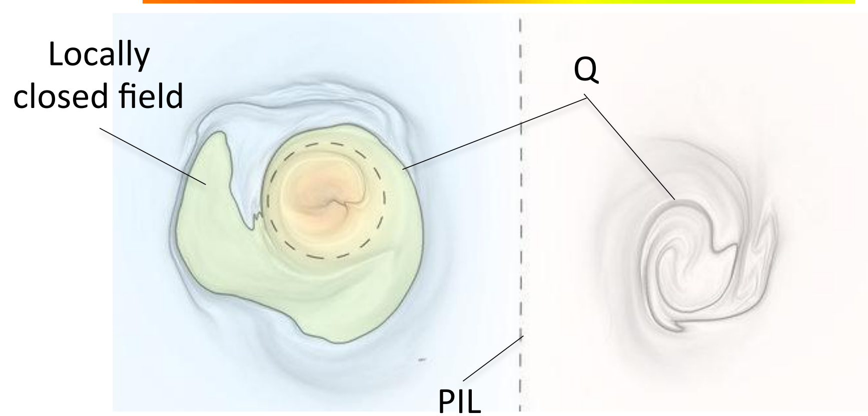
$$Q = \frac{B_n^*}{B_n}\sqrt{\left(\frac{\partial X}{\partial x}\right)^2 + \left(\frac{\partial Y}{\partial x}\right)^2 + \left(\frac{\partial X}{\partial y}\right)^2 + \left(\frac{\partial Y}{\partial y}\right)^2}$$

$$Q \in [2, \infty)$$

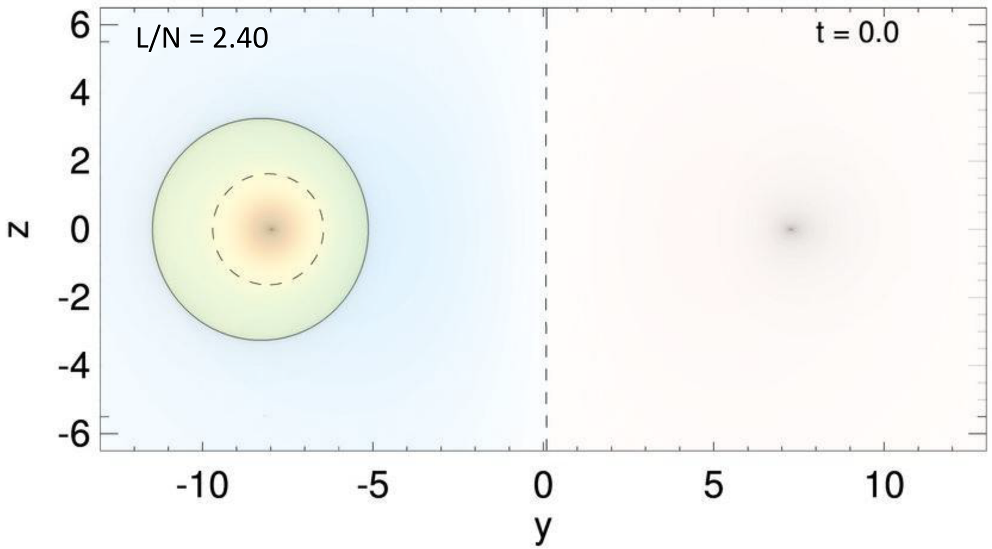
- Shows how squashed/stretched an elementary flux tube becomes.
- Infinite across separatrix surfaces, and high in Quasi-Separatrix Layers (QSLs).

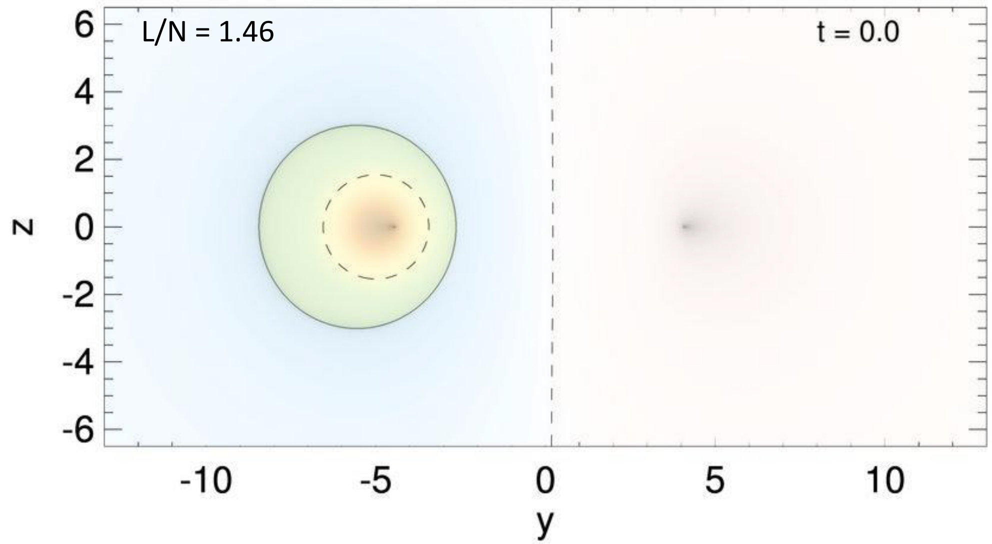
- Moving Q layers show the footprint of reconnection flux fronts (Titov et al. 2008).
- In flares: moving Q layers trace the flare ribbons (Savcheva et al. 2015).





Jets & Reconnection





PIL – dashed lines
red/blue – B_x (normal to photosphere)
green – locally closed field
grey – Q (squashing factor)

Long loop (L/N = 2.40)

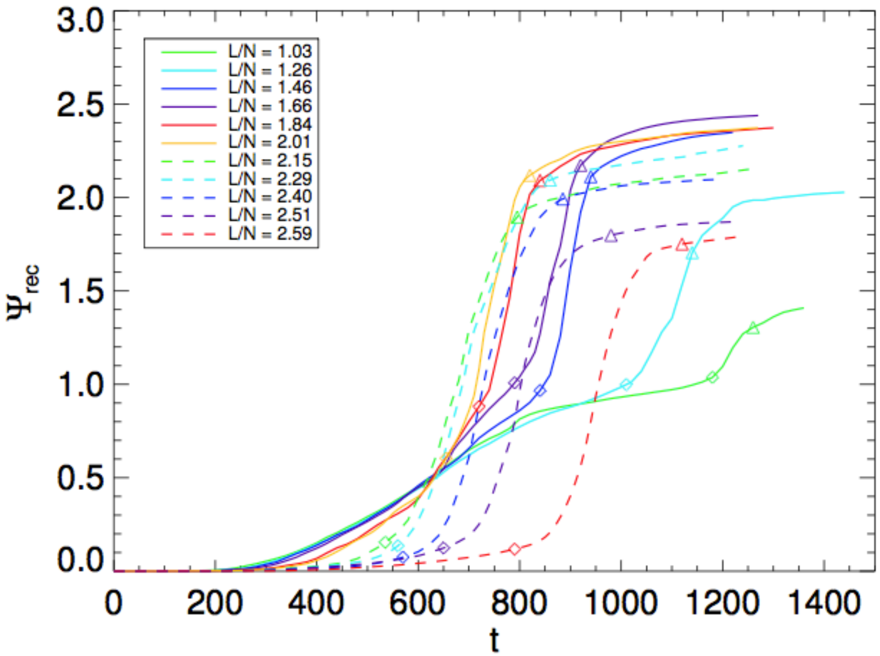
- Reconnection inhibited until symmetry is broken by the kink.
- Opens and closes twisted field during jet

Short Loop (L/N = 1.46)

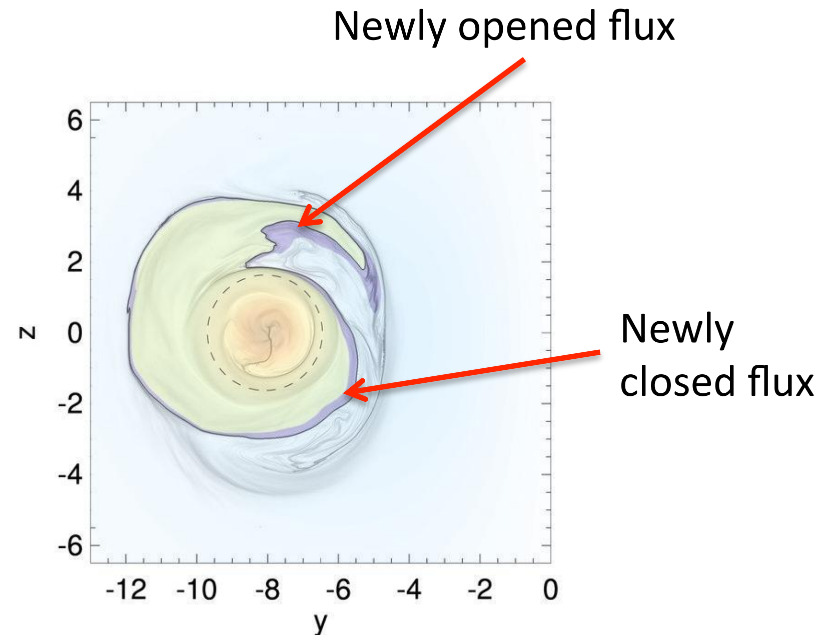
- Increased asymmetry = steady slow reconnection before jet.
- Twisted field opened before jet.
- Closed during jet.

Quantitative Differences

Normalised reconnected flux



Normalised flux = number of dome's worth.



$$\Psi_{rec}(t) = \frac{1}{2}\sum(\Delta\Psi_{opened} + \Delta\Psi_{closed})$$

L/N > 2.1

- Negligible reconnection before jet.
- ~ all dome flux opened & closed during jet.

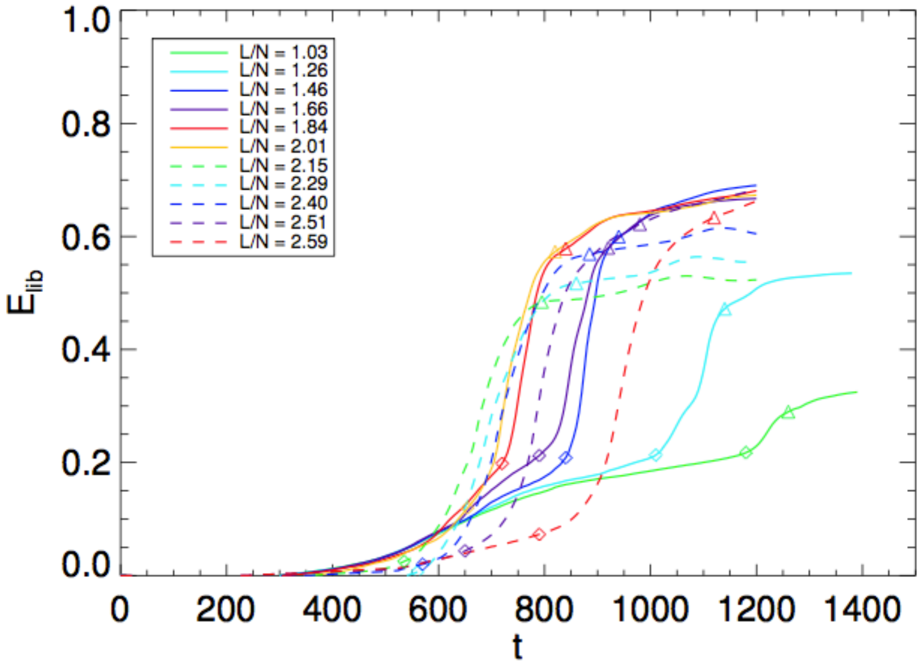
L/N < 2.1

- Up to all the dome flux opened up.
- Roughly all dome flux closed during jet.
- Lowest L/N: weak jets & reflected flows.

Most configurations: Ψ_{rec} ~ 2 in total -> flux opened & closed

Quantitative Differences

Liberated energy (normalised)



$$E_{lib}(t) = E_{inj}(t) - \Delta E_{mag}(t)$$

Energy liberated from the magnetic field

Energy injected by driving

Energy stored in the magnetic field

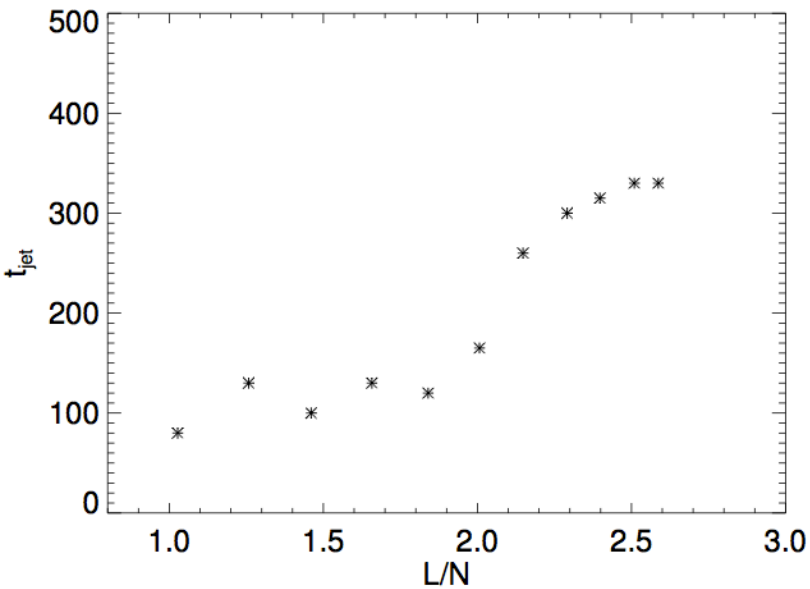
L/N > 2.1
- Little energy release before jet.

L/N < 2.1
- Up to ~20% energy released before jet.

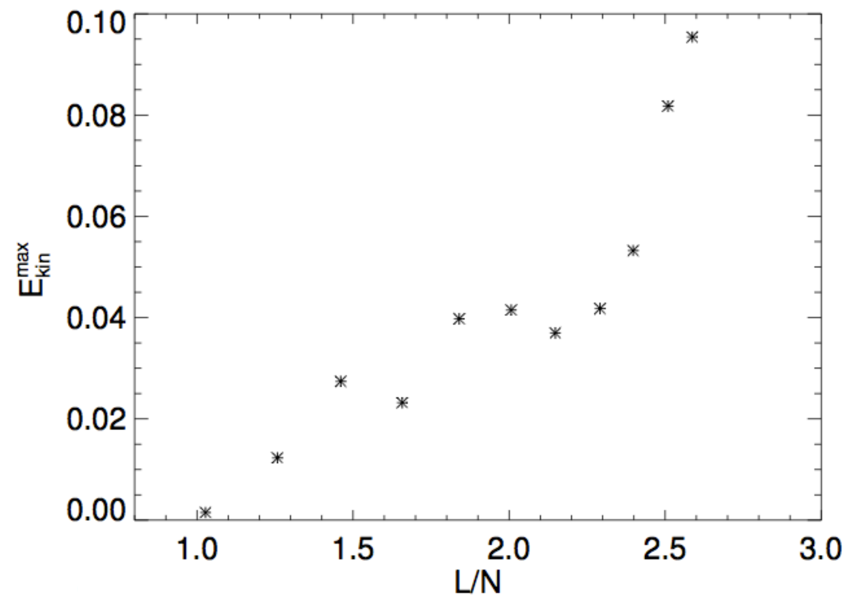
Most configurations: ~ 50%-60% injected energy released in total

Quantitative Differences

Jet durations



Peak jet volumetric kinetic energies



Larger L/N – longer, more energetic jets.

- Greater energy stored before onset.
- Opening & closing of flux occurs during jet.
- Less interactions with reflecting flows.

Quantitative Differences

Observed Values (Shimojo et al. 1996, Savcheva et al. 2007)

Durations: a few mins – ~40 mins

Lengths: 10Mm – 100s Mm

Energies: ~10^{25} – 10^{28} ergs

Velocities: 100's – ~1000km/s

Scale to typical active region values using:

$E_{kin} = E_s E'_{kin}$, $v_{jet} = V_s v'_{jet}$, $B = B_s B'$, $L = L_s L'$

where,

$V_s = B_s/\rho_s^{1/2}$, $t_s = L_s/V_s$, $E_s=(B_s)^2(L_s)^3$

Using scaling values of:

ρ_s= 1 x 10^{-14} g cm^{-3}, B_s= 10 G, L_s = 1 Mm

gives peak jet values of:

B_{pp} ~ 210 G, B_{back} ~ 40 G, L ~ 20 Mm, N ~ 7Mm

t_{jet} ~ 6 mins,

v_{jet} ~ 300 – 1000 km/s,

E_{jet} ~ 1 x 10^{28} ergs

E_{kin} ~ 1 x 10^{27} ergs

Conclusions

- The embedded bipole jet model reproduces a number of closed-field jet features:

    1. Observed untwisting motions along coronal loops.
    2. Expansion & contraction of the jet material along the loop.
    3. Quantitative match in terms of durations, velocities & energies.
    4. The trapping of twist within the loop where it relaxes.

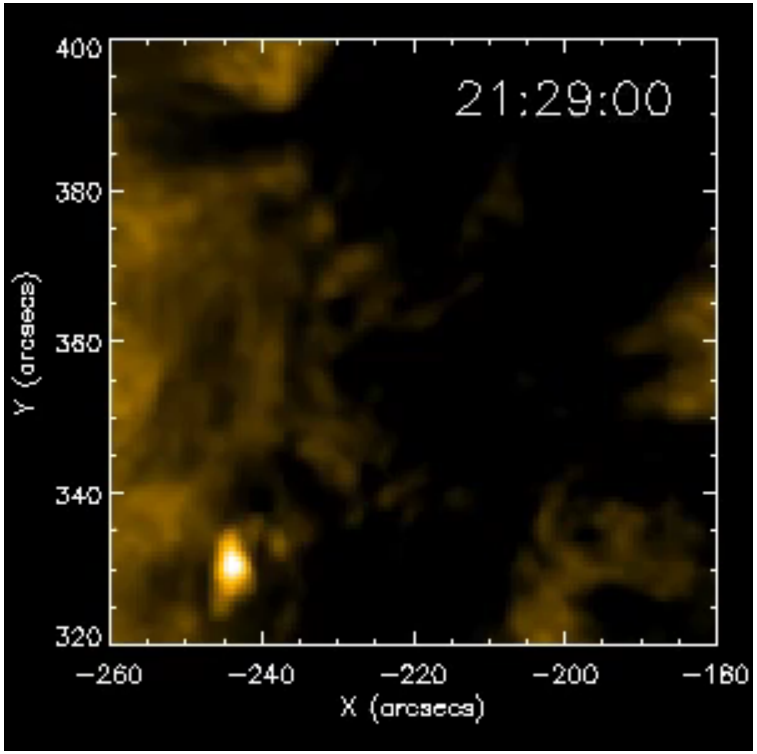
- The parameter study also revealed that:

    4. The relative size of jet region (N) vs loop separation (L) changes the jet behaviour.
    5. The longest, most energetic jets occur for large L/N.
    6. Jet reconnection is highly efficient!

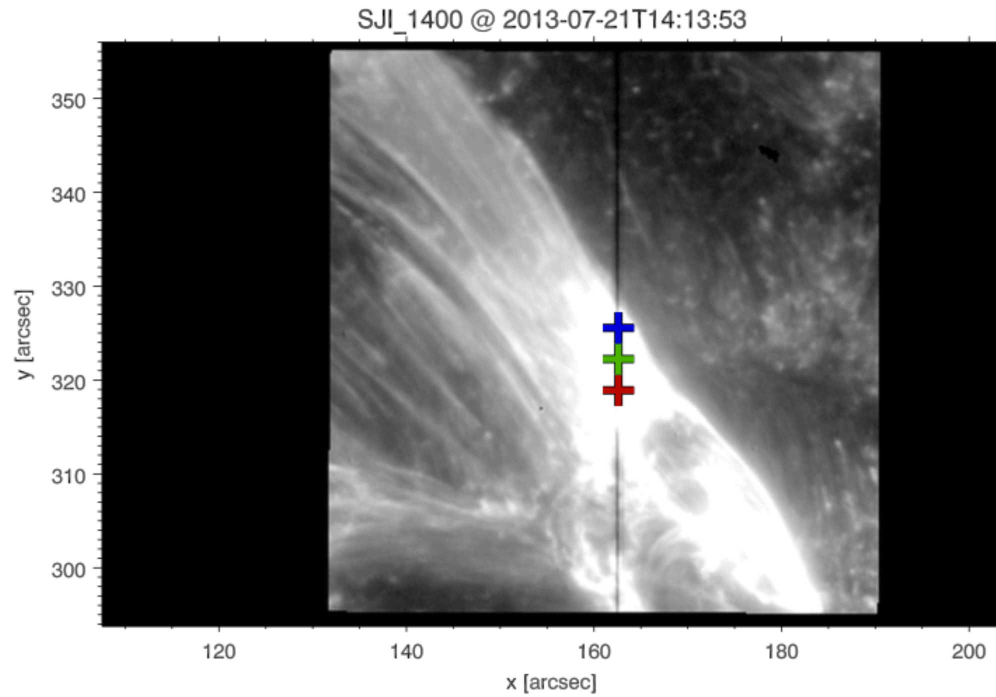
Wyper, P. F. & DeVore, C. R., *Simulations of Solar Jets Confined by Coronal Loops*, submitted to ApJ. (2015), [arXiv:1509.07901]

Tearing & Blobs

Zhang & Ji (2014)



Cheung et al. (2015)

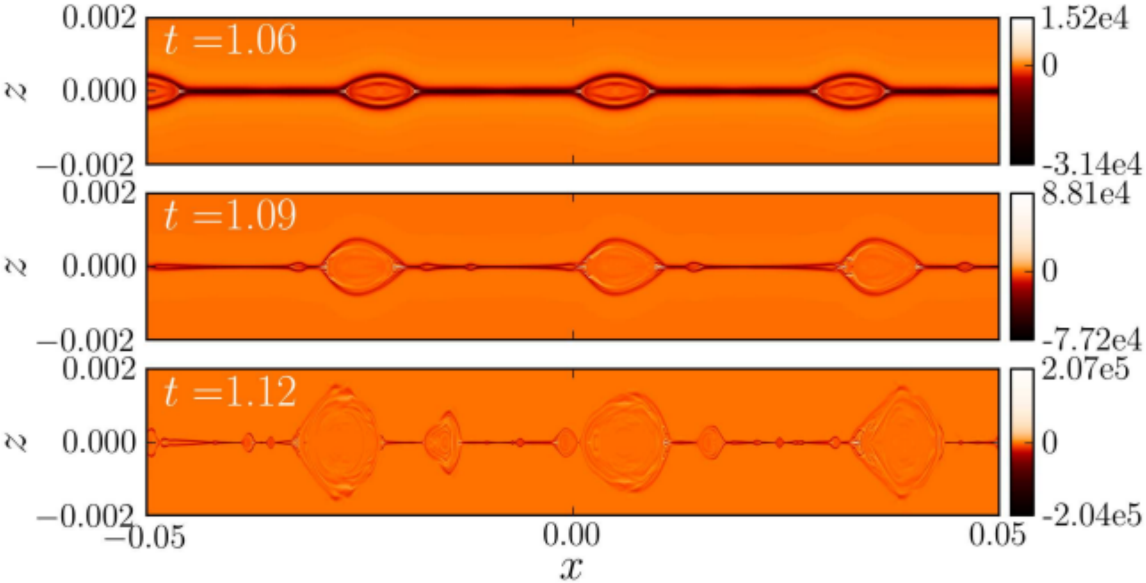


Blobs

- Enhanced temperature, density or both.
- Suggested that it's related to tearing of the jet current sheet.
- Does this suggest jet reconnection is bursty on very short time scales?
- Are blobs really from tearing or thermal instabilities?
- Is tearing even expected to occur?

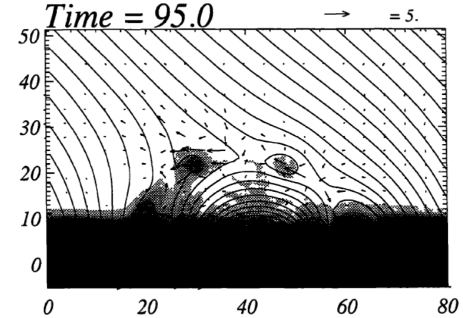
2D Tearing: Plasmoid Instability

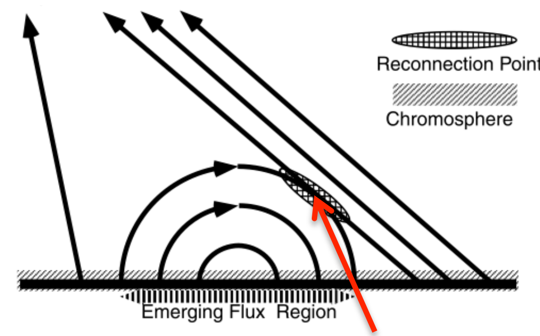
Huang & Bhattacharjee 13



2D Jets

Yokoyama & Shibata 96





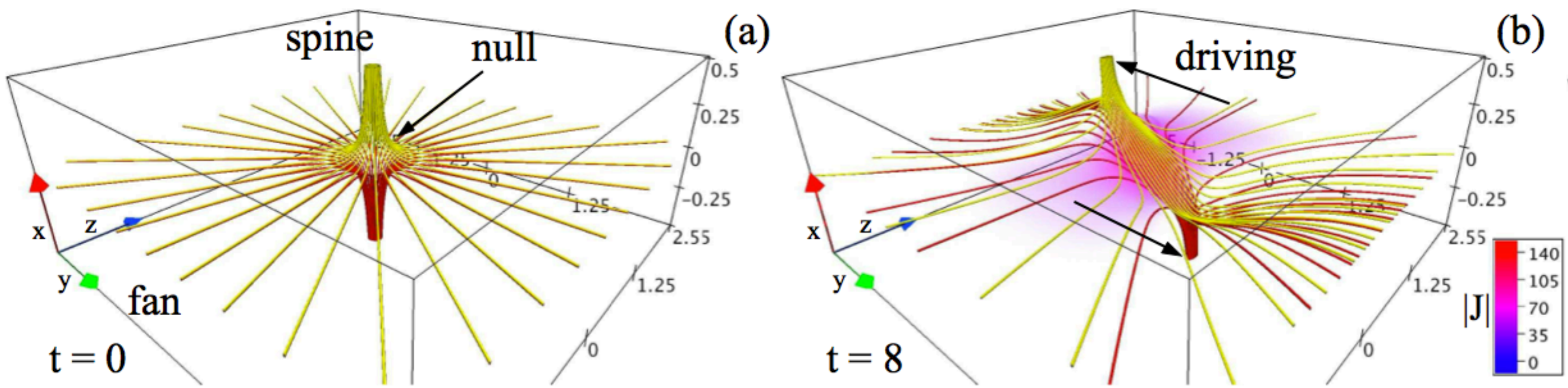
Current layer at a 3D null

The Plasmoid Instability

- Tearing occurring in Sweet-Parker current layers (long and thin).
- Fluctuations grow faster than ejection time when: $S = L v_a/\eta > S_c \sim 1 \times 10^4$
- Linear growth rate ~ $S^{1/4}$ -> very fast in the corona!
- Quickly non-linear, forming islands that coalesce and are ejected -> blobs?

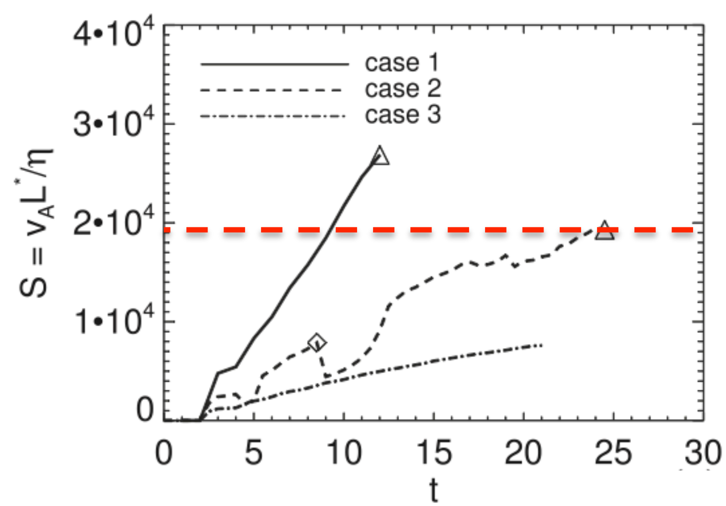
- But jets are 3D! No flare-like symmetry planes here…

3D Tearing: Null Point Current Layer



Wyper & Pontin (2014a)

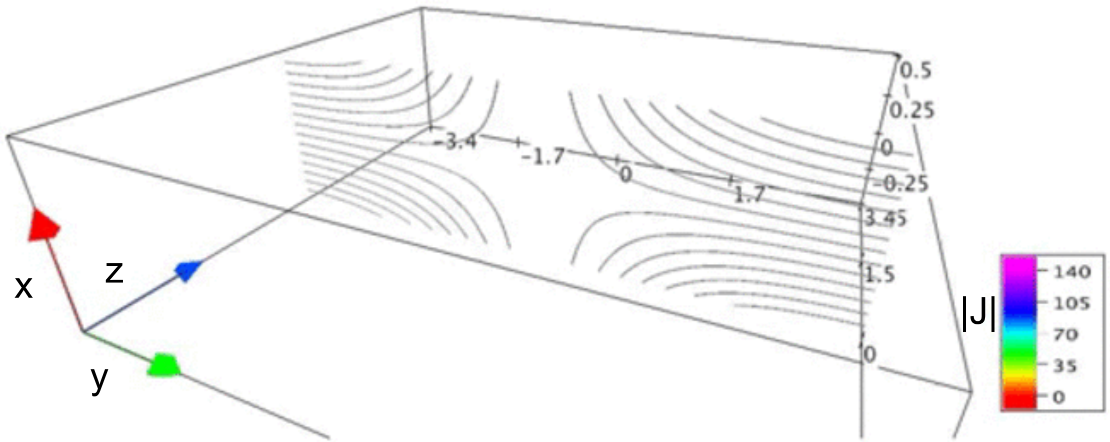
- Sheared a 3D null, forming a current layer.
- Explicit η used.
- Continued until tearing occurred.
- Unstable for $S_c > 2 \times 10^4$ (S measured in plane of spine-fan collapse).
- Current layers formed at 3D nulls explosively unstable to tearing at coronal values.

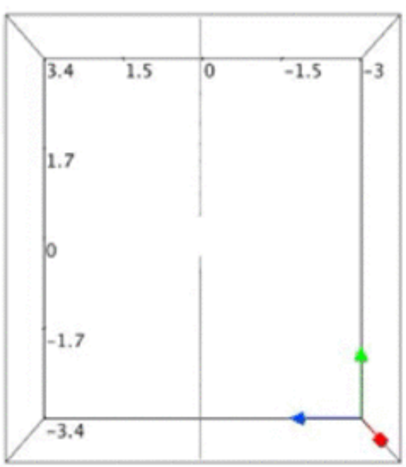


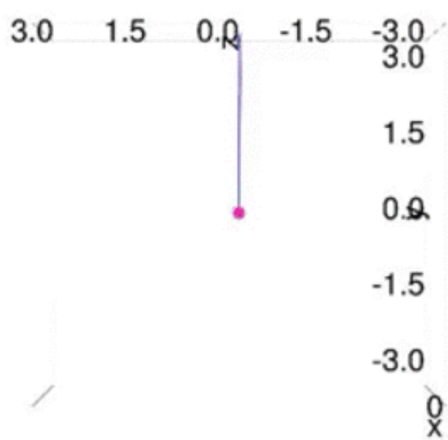
-> Jet current layers should be explosively unstable to tearing.

3D Tearing: Null Point Current Layer

Wyper & Pontin (2014b) – Non-linear Dynamics

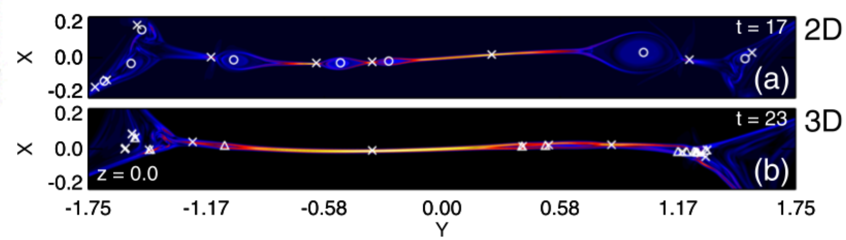




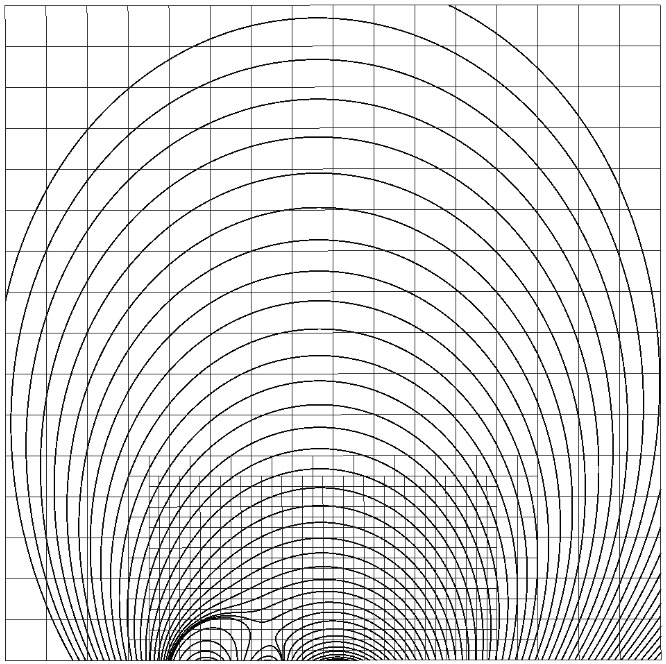


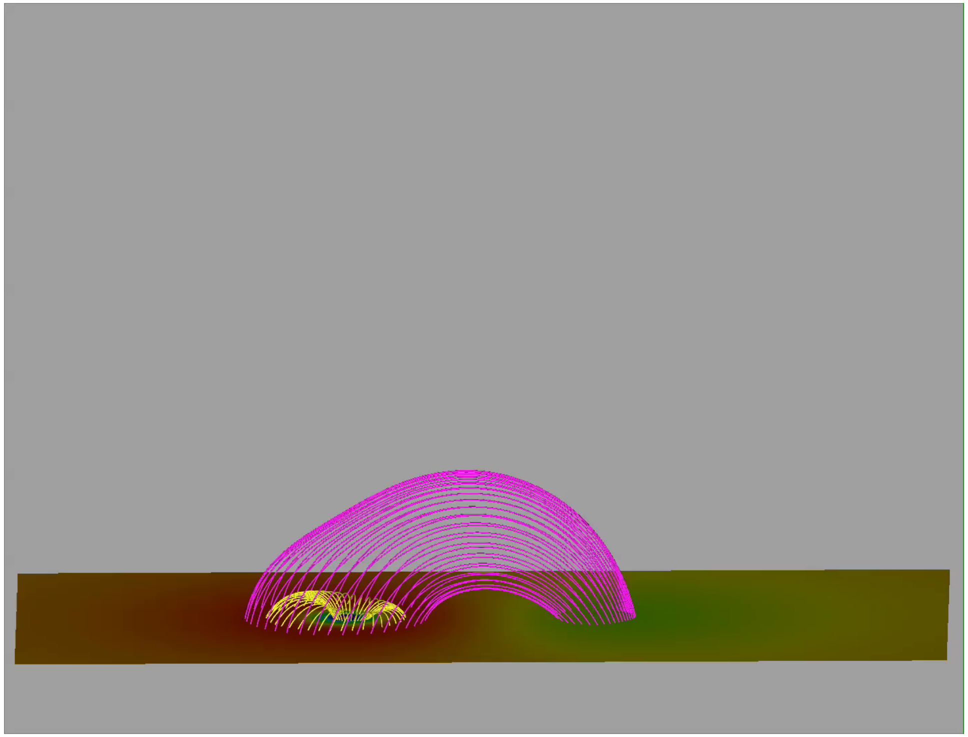
Main Features

- Forms flux ropes & multiple null points.
- A complex relationship exists between the two.
- Flux ropes kink and writhe in weak field near the centre.
- Flux ropes expel twist as torsional waves at an angle from the outflow.
- Expulsion of twist/mass flattens flux ropes vs 2D islands -> no blobs?



High Resolution Simulations

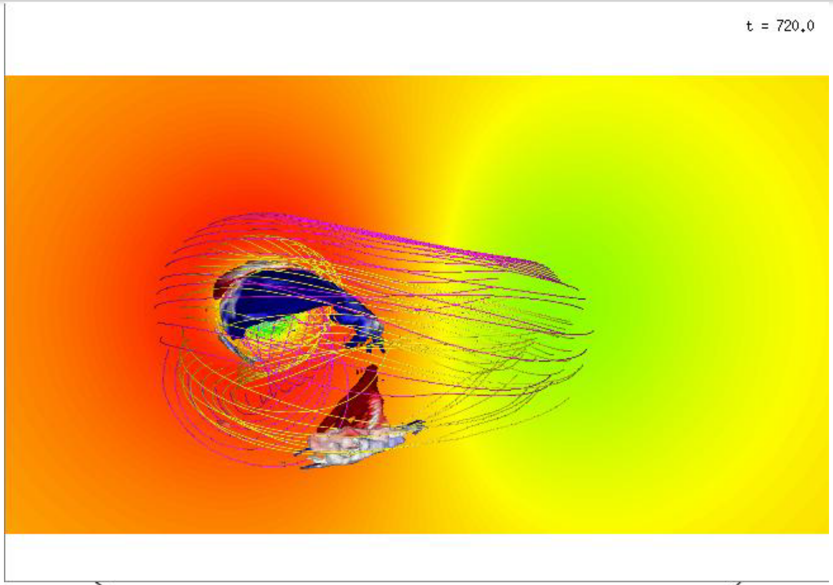


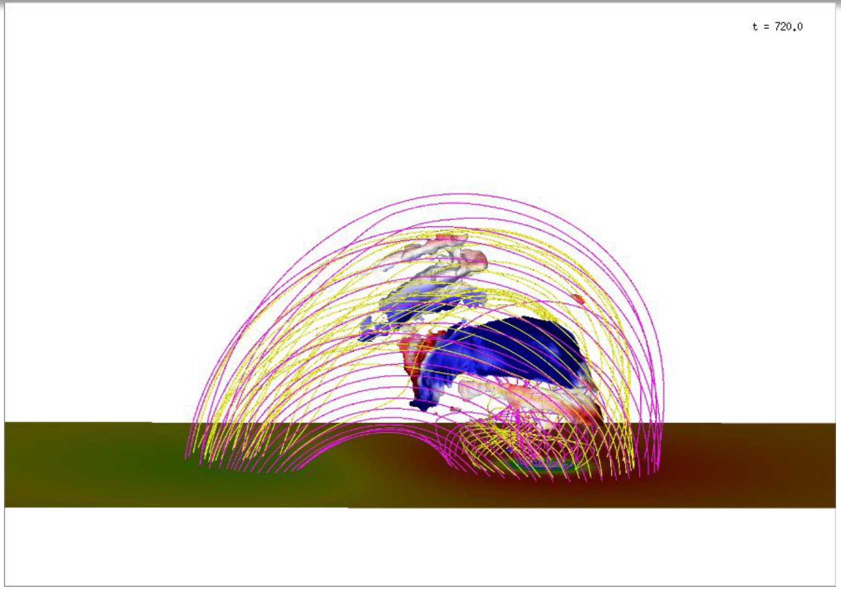


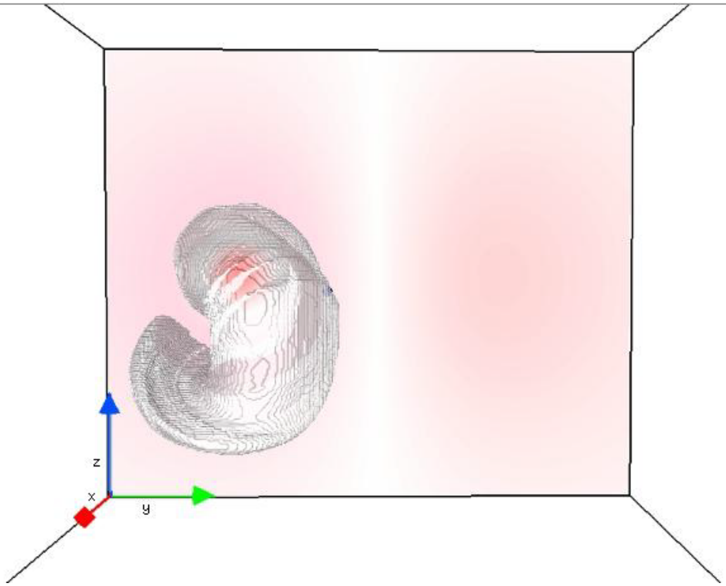
- Each cell contains 8x8x8 grid cells.
- Blocks of fixed increased resolution so that tearing not due to changing grid adaption.
- Increased effective Lundquist number.

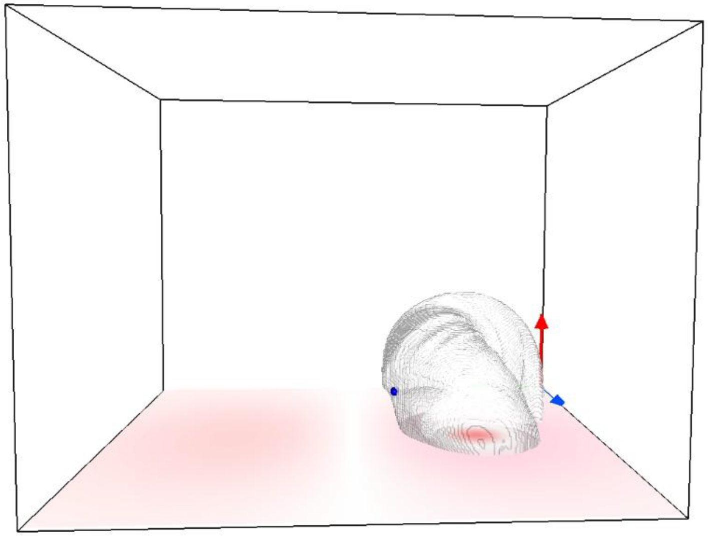
- Similar qualitative features.
- Much greater structure in the loop (previously smoothed out).
- Is there tearing?

Short Loop: Tearing

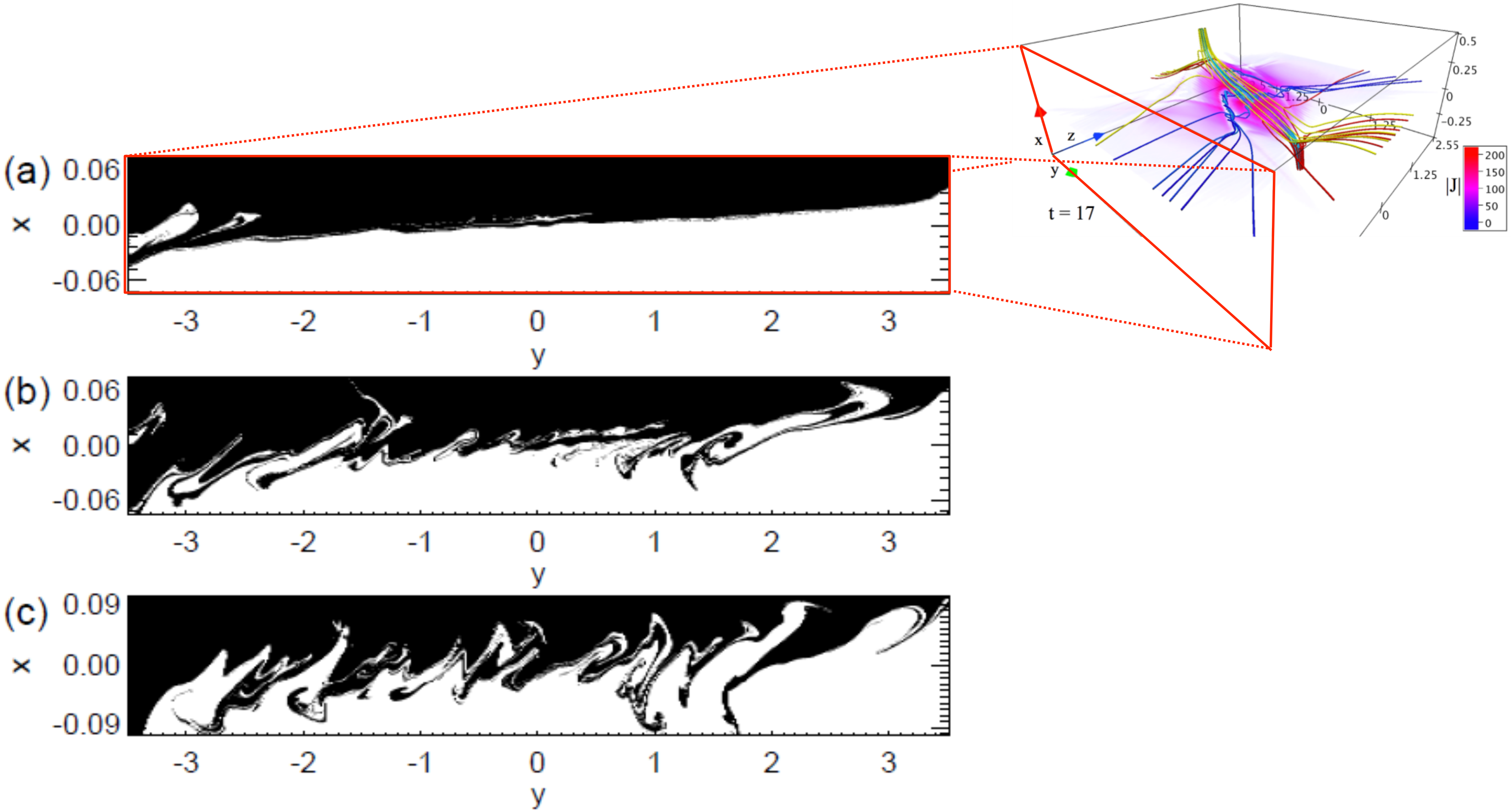








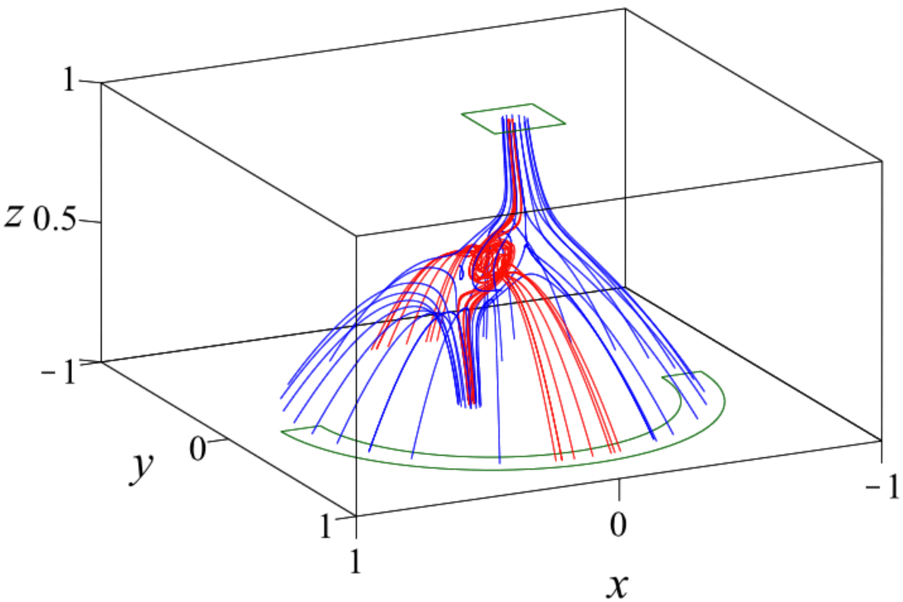
Photospheric Signatures

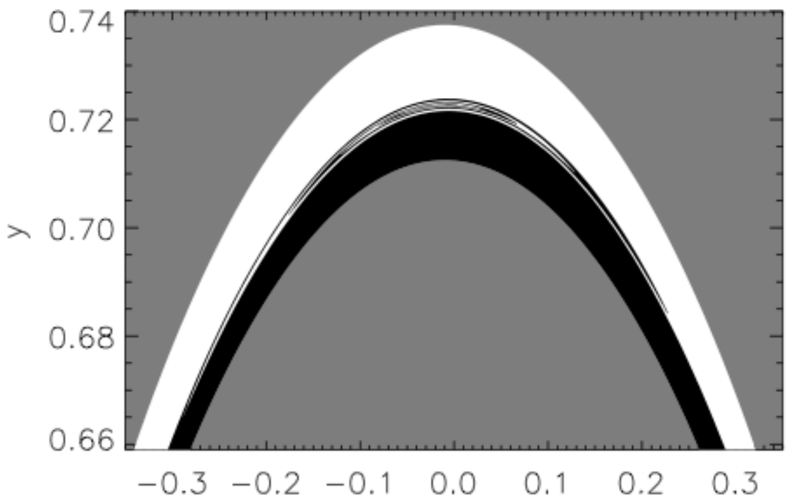


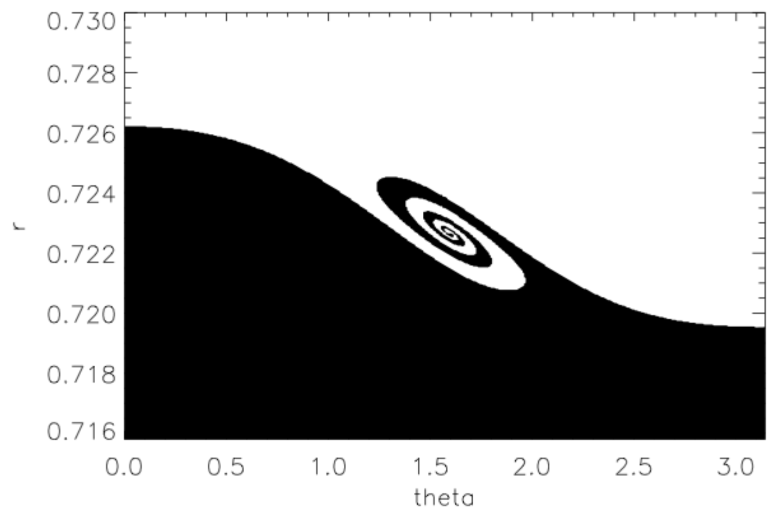
- Trace field lines from side plane. Colour point according to whether field line hits top or bottom boundary.
- Flux ropes twist up the separatrix boundary – reconnecting flux back and forth.
- Creates spiral patterns in the mapping.

Photospheric Signatures

Pontin & Wyper (2015) – Jet Topology





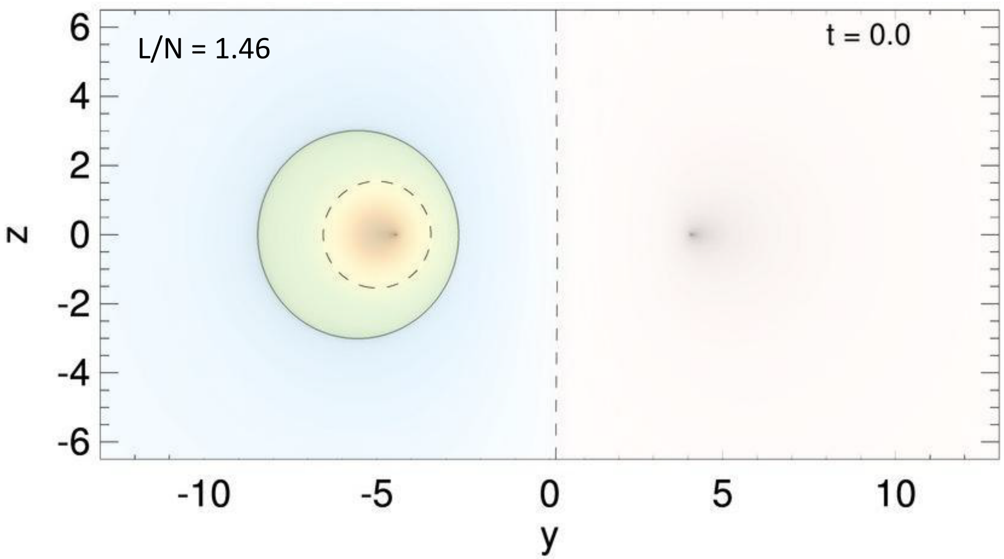


- Static analytical model.
- Potential field + local twist region.
- Rough approximation to tearing.

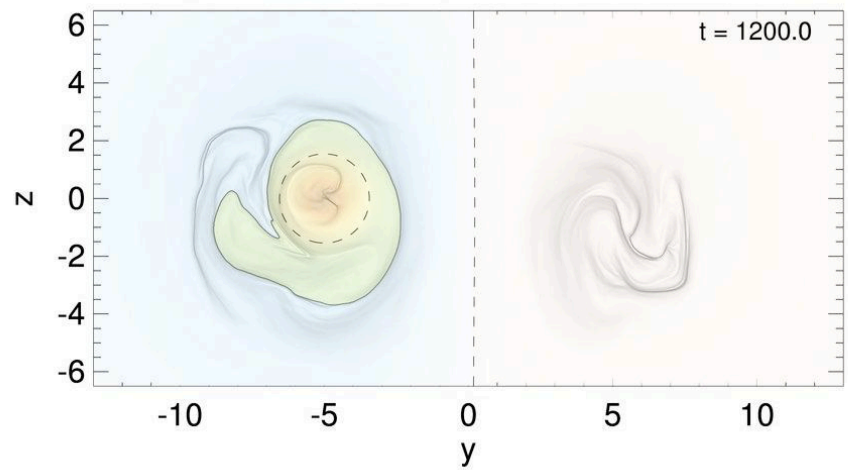
- Flux rope footpoints = extended twisted open-closed mixed layer.

→ should give spiral patterns in Q

Photospheric Signatures



Lower resolution



- The biggest flux ropes appear as spirals in Q.
- Here Q layers coincident with high current.

Conclusions

Tearing

- Tearing occurs at higher resolution/Lundquist numbers in jet simulations.
- Expected to occurs in all observed jets to some degree -> since all jets involve open-closed field reconnection across an extended 3D null current layer.

Reconnection Region

- Multiple 3D null points and flux rope structures.
- Flux ropes are ejected as untwisting wave packets that feed into the jet outflow/curtain.

Photospheric Signatures

- The biggest have a spiral photospheric signature in Q (and J).

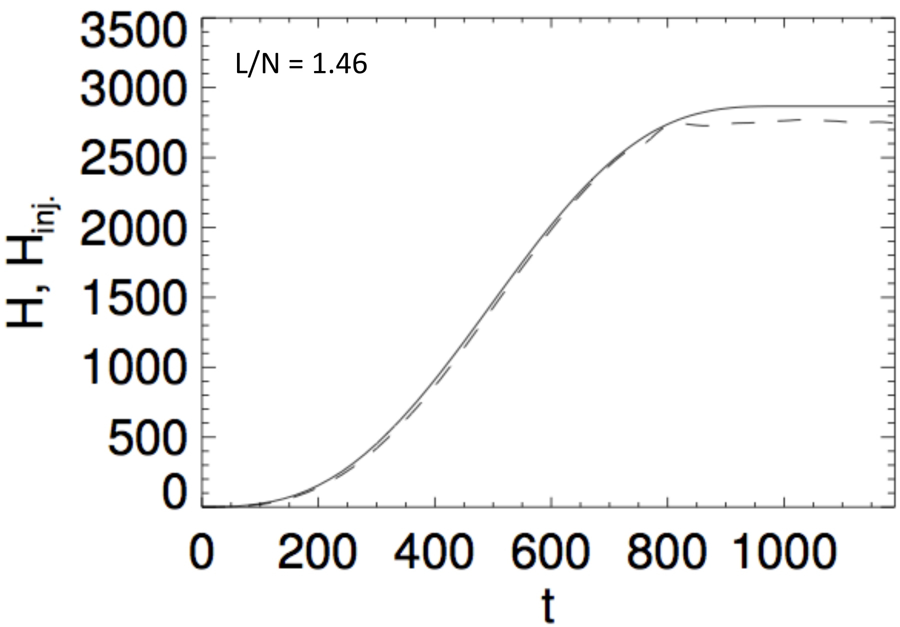
Big question: is this what we are seeing as blobs?

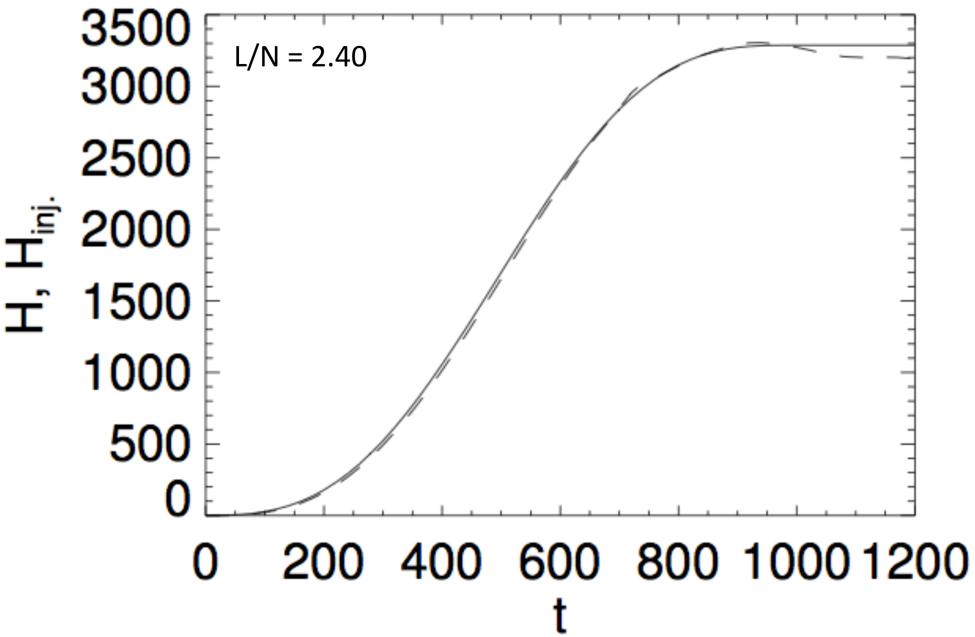
- Not clear!
- Need much improved energy equation, gravitational stratification etc to answer.
- Could it still be observed even if not?

Thank you!

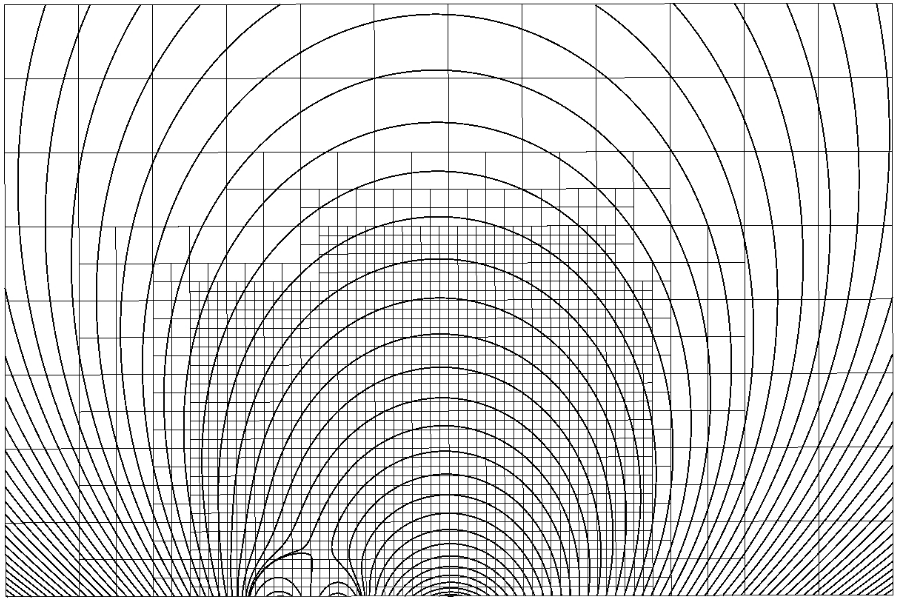
Extra

Helicity Conservation

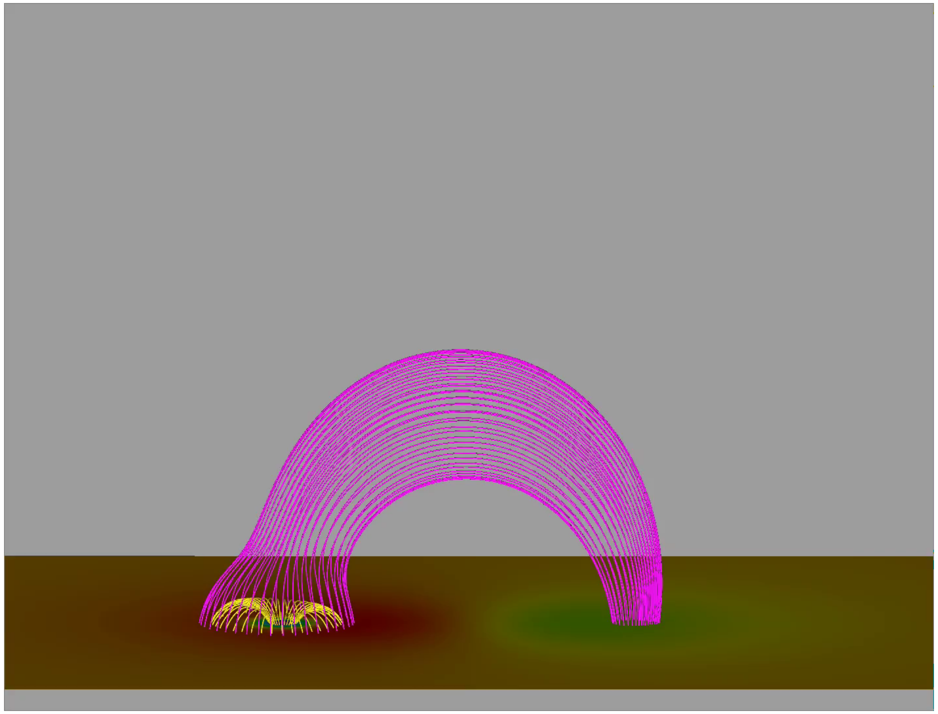




High Resolution Simulations

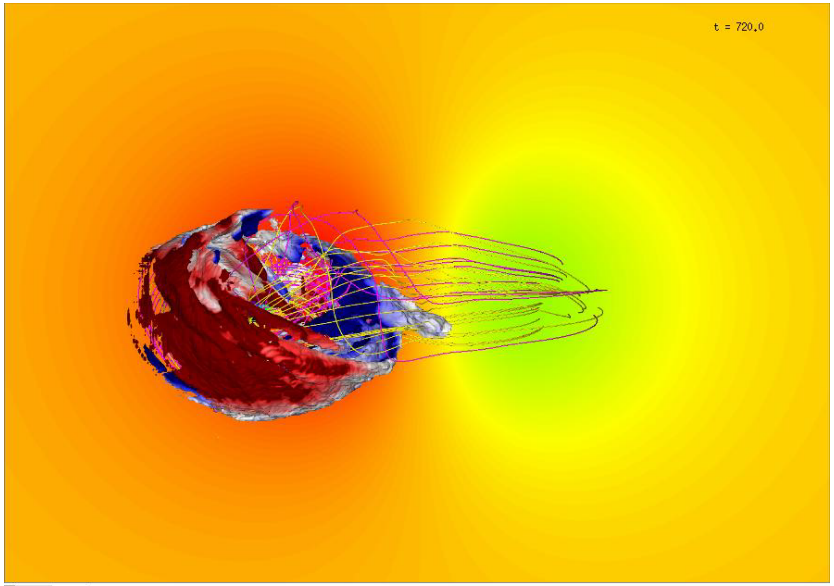


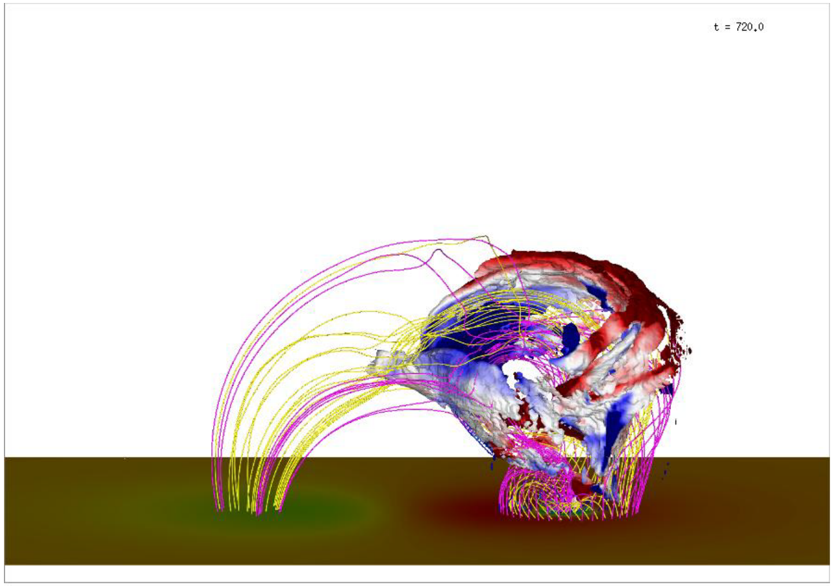
- Each cell contains 8x8x8 grid cells.
- Blocks of fixed increased resolution so that tearing not due to changing grid adaption.
- Increased effective Lundquist number of current layer.

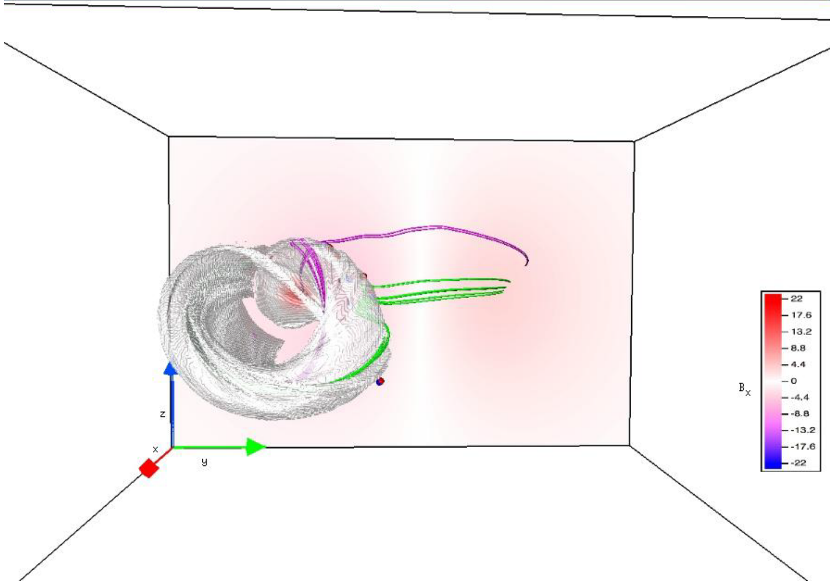


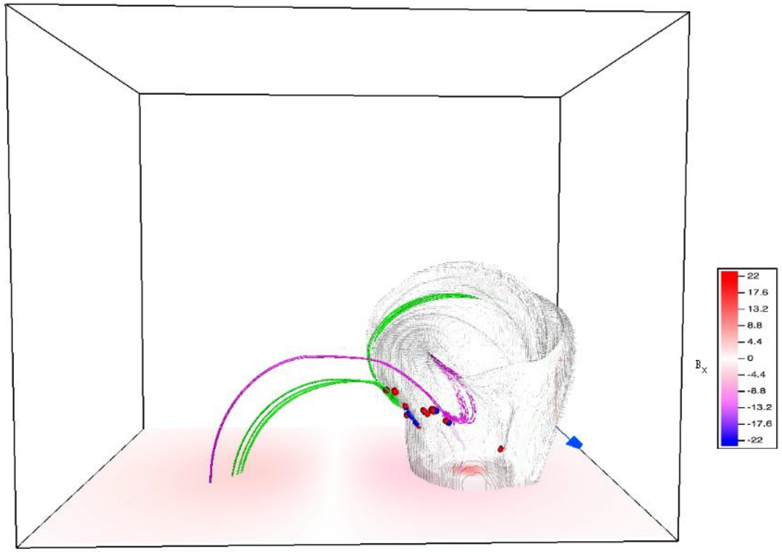
- Similar qualitative features.
- Now much greater fine-scale structure in the loop (previously smoothed out).
- Is there tearing?

Long Loop: Tearing

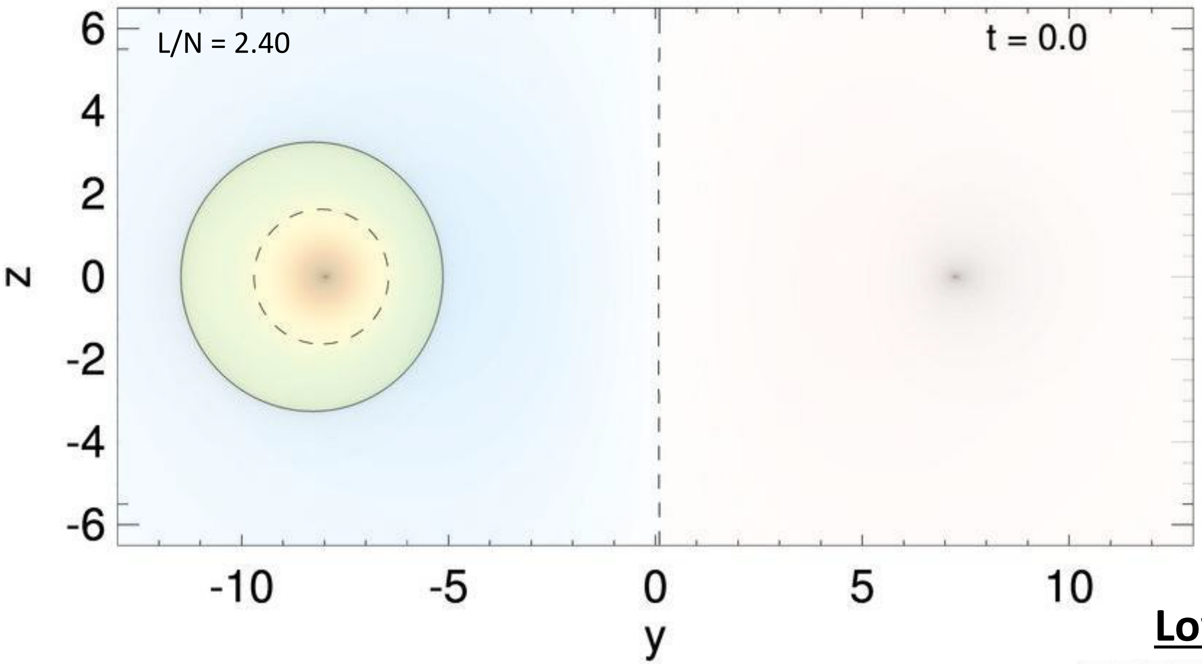




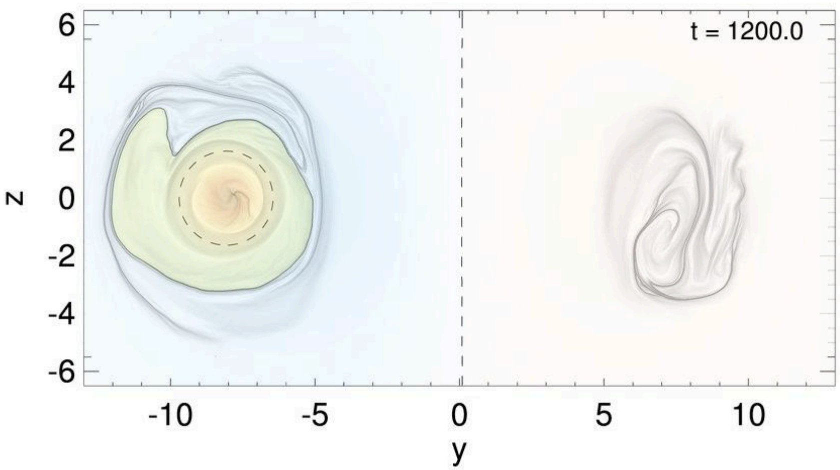




Tearing Signatures



Lower Resolution



- Some spiral signatures.
- Only the most broad ropes make an impact.